HEIGHT ESTIMATION USING MATCHED TERRAIN PROCESSING

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SBIR Phase I Contract Number: F30602-C-0133

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ABSTRACT

ORINCON has developed a family of predictive propagation environment signal processing techniques under the proprietary umbrella term *matched terrain processing* (MTP). The MTP techniques are knowledge-aided approaches that exploit new generations of high-spatial-resolution geospatial databases, such as DTED, LULC and RF bistatic backscatter characterization tables. The MTP approach was first successfully demonstrated by passively intercepting signals (including their interactions with surrounding terrain) from a ground-based emitter, to geolocate the emitter using a single airborne platform (normally requiring multiple platforms).

During a Phase I SBIR effort, we successfully demonstrated a proof-of-concept complementary MTP approach that featured a specific scenario where approximately level 4 DETD data was combined with data from an active radar collection platform in which backscattered signals returning from a passive low-flying aircraft and the surrounding terrain were successfully used to estimate the height of the low-flying target (normally not possible from a single asset due to the broad elevational beam-pattern of the collection aircraft antenna which normally lacks significant vertical aperture).

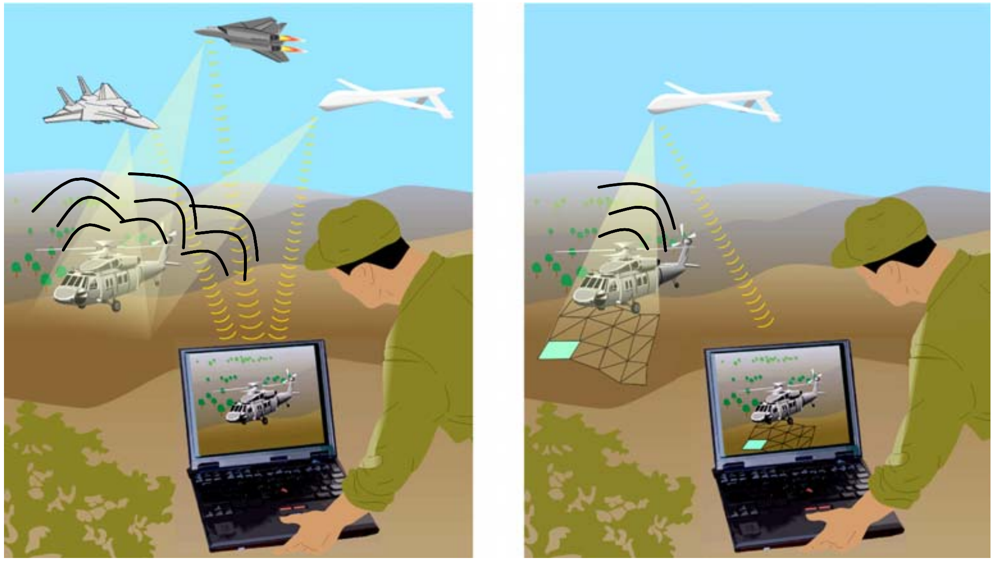
Our preliminary phase I results show that the correlation procedure peaks at the proper height, however the number of patches has a significant influence on the correlation procedure and the computational complexity of estimating the height model waveforms.

INTRODUCTION

Accurately detecting, tracking, and prosecuting low, slow flying airborne targets is a primary mission for future ISR sensor systems, particularly UAVs like Global Hawk, Predator, and the future SensorCraft. The future for antenna arrays on such unmanned aircraft is to embed the antenna array elements directly into the airframe, creating conformal distributed antenna apertures on the surveilling aircraft. Because aircraft tend to be much longer along the fuselage and across the wing span than they are in height (and often there is very little vertical height in the tail), any antenna array apertures conformal to the airframe or along the wings will have very good azimuthal (bearing) spatial resolution in the horizontal plane formed by the wings and fuselage, but poor elevational spatial resolution in the vertical plane orthogonal to this horizontal plane. Thus, it is not usually possible to obtain precision target aircraft altitude estimates due to the low elevational spatial resolution on the sensor aircraft. By maneuvering the sensor aircraft through altitude variations and noting the trajectory changes, it is possible to create an elevational synthetic aperture due to the maneuvering to improve elevational spatial precision, this is not practical as it is desirable to maintain the sensor aircraft in level flight while operating the sensors. Thus, the Phase I effort focused on the one-dimensional kinematic problem of finding the height of the target aircraft.

Figure 1 illustrates the advantage of the use of the MTP for field applications by reducing the number of assets and using terrain data to estimate the altitude of the target. Normal prosecution of a threat low-flying aircraft requires detection and estimation of its kinematic parameters (location, speed, direction), which typically requires multiple surveillance aircraft using radars using traditional time-difference-of-arrival (TDOA) and frequency-difference (Doppler)-of-arrival (FDOA) methods to locate and track the target. These multiple aircraft do not exploit the power of knowledge-aided kinematic estimation. The MTP does use such information, and the result is that a single surveillance aircraft can provide all kinematic estimates. Clearly, deploying multiple aircraft and fusing their various measurements and estimates is significantly more operationally complex and difficult than working with a single surveillance aircraft to detect and track a low-flying airborne target.

Our approach stems from using a Knowledge Aided (KA) signal processing Technique called Matched terrain Processing (MTP), a proven technique when the target in ground based and emitting, and we extended, this technique from first principal, to be applied to slow, low flying aircraft. Our Phase I project main objectives were to create a scenario using digital terrain elevation data (DTED) terrain map, realistic backscatter characteristics, a source which was a Predator UAV, the target was a helicopter. Our approach was to develop a MTP algorithm that would output a height estimation based on the received waveform.



(a) (b)

Figure 1. Operational advantage using single surveillance aircraft incorporating MTP techniques over multiple surveillance aircraft employing traditional kinematic estimation algorithms to detect and to track low, slow flying aircraft.

The algorithm depended on a composite waveform consisting of the superposition of 4 waveforms described bellow.

1. Direct ray on transmit and direct ray on receive (D-D)
2. Direct ray on transmit and ground reflected ray on receive (D-R)
3. Ground reflected ray on transmit and direct ray on receive (R-D)
4. Ground reflected ray on transmit and ground reflected ray on receive (R-R)

Figure 2 shows waveforms 2,3,4 interacting with a single terrain point, where as ours uses a grid of terrain patches.

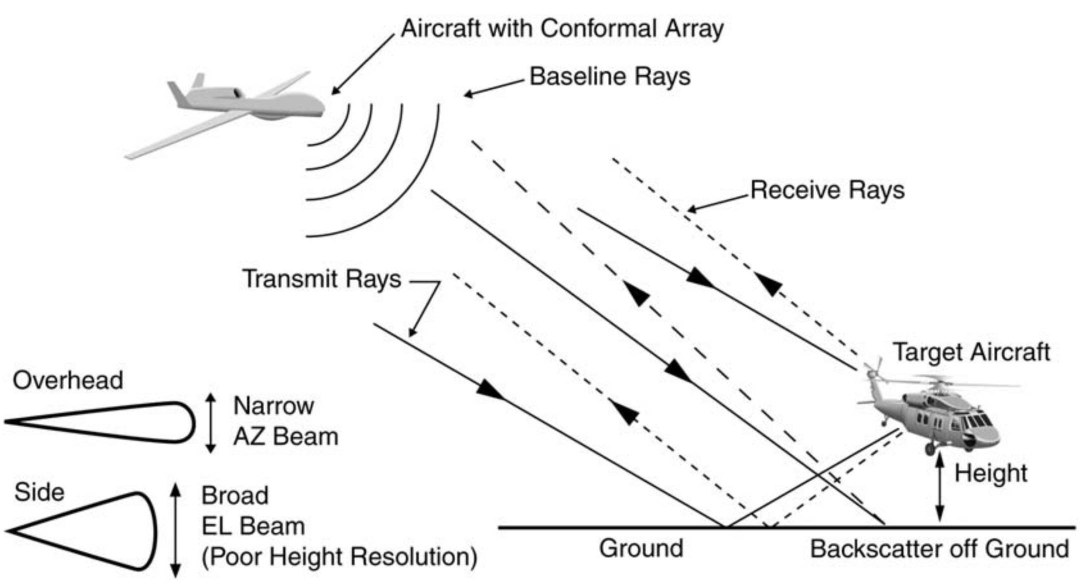


Figure 2. Direct path and micro-multipath propagation for an aircraft target showing bistatic specular reflections local to the aircraft assumed height estimation techniques. Note the poor elevation beam resolution of the sensor aircraft with the conformal array that makes direct estimates of the target aircraft altitude not possible.

The balance of this paper organized as follows: the next section describes the scenario which include parameters of the target, source and which DETD site that was chosen and validating our assumption on homogeneous terrain backscatter characteristics. The third section briefly describes the algorithm formulation. The fourth section describes the simulation results and summing up with a conclusion and future work.

SCENARIO DESCRIPTION

To formulate the scenario we evaluated three different possible land sites as seen in figure 3, the first being Provo Canyon, Utah the second being Ft. Irwin, CA and a third was Point of the Mountain in Utah, where we have previously flown actual aircraft experiments. Some of the DTED data used required filling in the gaps by interpolating with coarser resolution USGS DEM data.

After investigation of the three candidate sites, we decided on Point of the Mountain, due to a previous project experience at this location where an actual field test was performed using a different MTP algorithm. Figure 4, gives an aerial perspective of where Point of the Mountain is relative to physical land marks and where the DETD data is. We also use terrain photos to help justify the homogeneous terrain, seen in Figure 7, and the assumed choice of terrain backscatter coefficient to be used in the MTP algorithm.

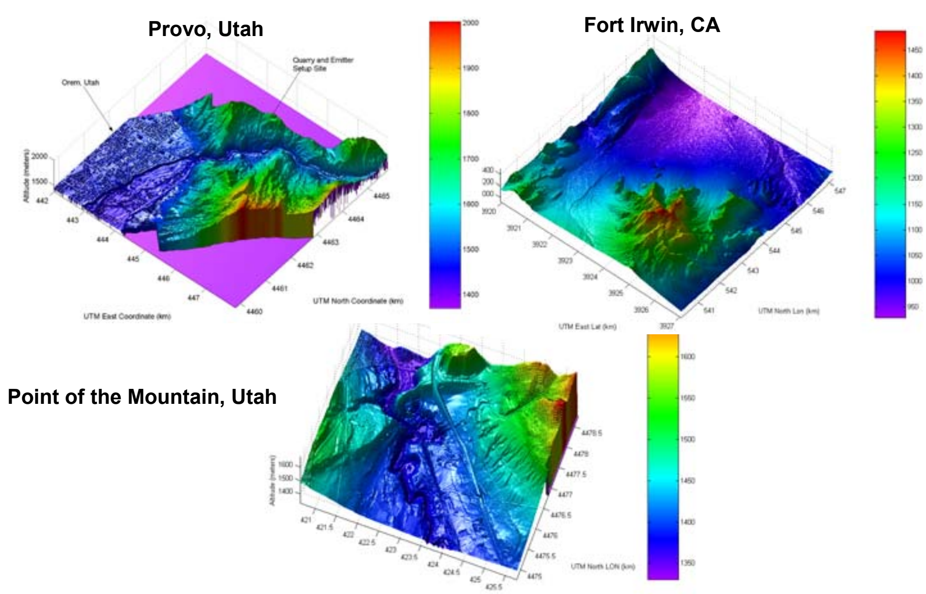


Figure 3. DTED 3-D rendering of Lucky Rise NTC, Ft. Irwin, CA collection site.

The scenario for the phase I has a source platform being an Unmanned Aerial Vehicle (UAV), specifically a RQ-1 Predator, and the target being a helicopter, each traversing the scene as shown in Figure 5. The operational parameters for the source and target in this scenario are given in Figure 6. Figures 7 give an actual view of the terrain to validate the choice of backscatter reflectivity, in this scenario where we are using rocky/grassy terrain backscatter model. For our scenario will be to take a point along the trajectories and use a 5-10 microsecond interval about delay of the direct return (path 1 above). For the phase I we will only look at a single pulse and perform the correlative procedure to this scenario.

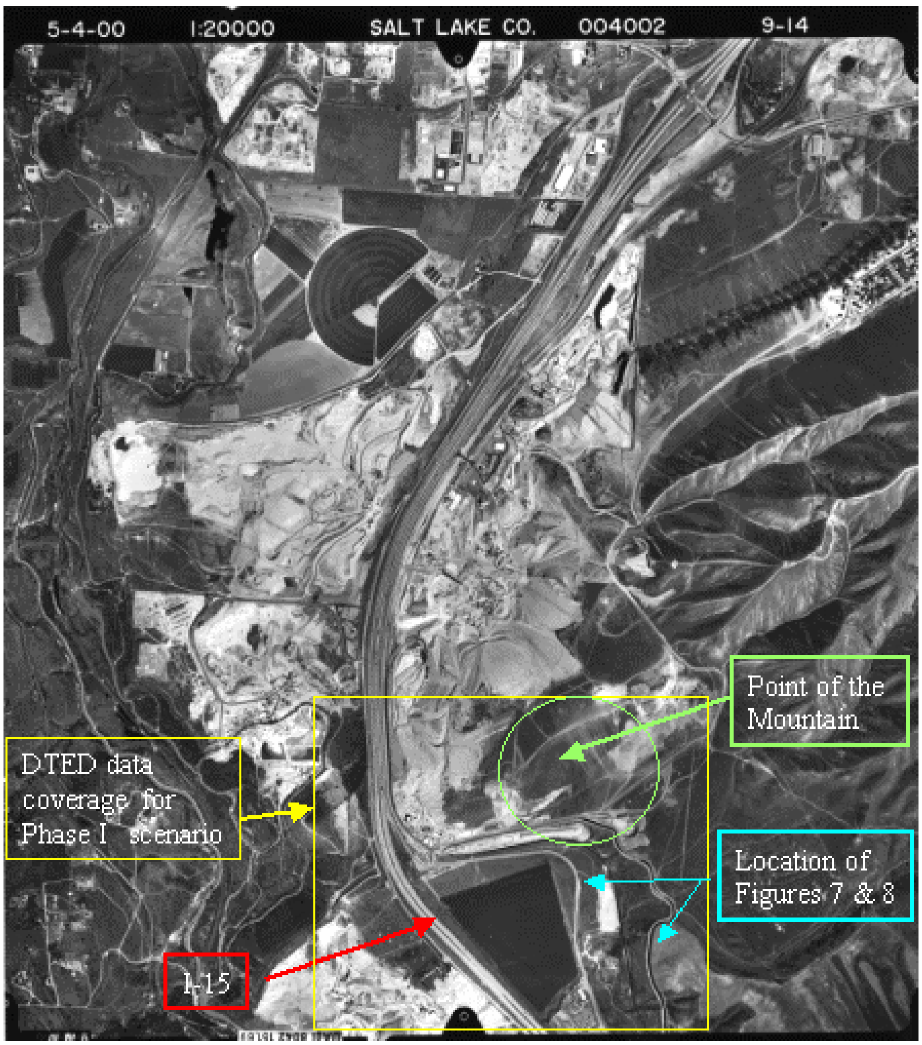


Figure 4. The overall depiction of the scene used in our Phase I scenario. The red arrow point to I-15 passing though the valley, the yellow square shows the area for which we have DTED elevation data of Point of the Mountain. Point of the Mountain is shown in green and is a clear landmark in Figure 6. The blue arrows give a perspective of the terrain around point of the mountain.

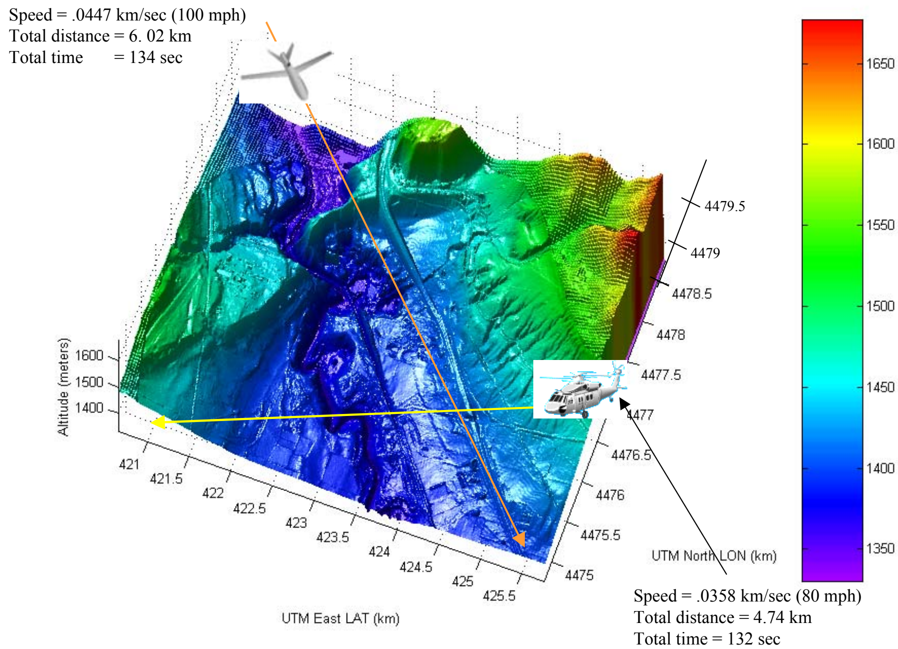
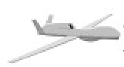


Figure 5. The proposed scenario for Phase I is to use top of the mountain DTED data with a UAV and helicopter. The UAV is traversing over the yellow line at a height of 3500 meters at a speed of 10 mph while the helicopter is at an altitude of 1550 meters while traveling at a speed of 80 mph.

Source 

- Position
  - Initial
    - 4479.5 NL km, 421 EL km,
    - 3500 m height
  - End position
    - 4475 NL km, 425 EL km,
    - 3500 m height
- Total distance
  - 6.02 km
- Velocity
  - 44.80 m/s (100 mph)
- Radar parameters
  - f = 10 GHz
  - Pulse duration = 100 ns (10 MHz BW)
  - # Pulses = Single Pulse
  - PRI = 1000

Target 

- Position
  - Initial
    - 4477 NL km, 425.5 EL km,
    - 1550 m height
  - End position
    - 4475 NL km, 421 EL km,
    - 1550 m height
- Total distance
  - 4.74 km
- Velocity
  - 33.84 m/s (80 mph)

Figure 6. The scenario parameters for the UAV and helicopter

(a) (a)

(b) (b)

Figure 7. The figure on the left side shows the terrain in the valley around Point of the Mountain is grassy with some rocks. From the picture of the terrain. While the figure on the right side is a hill just to the right of point of the mountain is also grassy with rocks. So we plan to use the table of backscatter coefficients associated with rocky/grassy terrain

MATCHED TERRAIN PROCESSING (MTP) ALGORITHM FORMULATION

The Matched Terrain Processing (MTP) technique couples signal reflectivity/scattering models with high-resolution geospatial databases backscatter (inferred from the LULC databases) to predict a bistatic response of a target illuminated by the radar emissions from the sensing aircraft. The MTP is so named due to the analogy of its processing steps to those of the underwater acoustics *matched field processing* (MFP) technique: match the observed multi-path signal to propagation environment conditions via a coherent correlation that determines the degree of match. The major functional dependencies that go into the MTP geolocation algorithm are:

1. Radar sensor and terrestrial emitter geometries and kinematics
2. Target RF emitter and antenna characteristics
3. Sensor receiver and antenna characteristics
4. Terrain and cultural feature characterization to fine-enough scale and quantification (elevation and backscatter databases)

By varying the assumed position, velocity, heading, altitude, etc., a number of possible bistatic responses can be estimated (height superpositioned waveform models) and correlated with the actual direct path and clutter signal received. The estimated position, velocity, heading, and altitude is the one that best correlates with and is most consistent for the actual received signal measurement (which includes direct path, strong multipath [specular echoes from a single terrain point], and clutter [diffuse echoes from a wide area of many terrain patches] components as illustrated in Figure 8). The MTP for the height estimation application is formed via three steps; estimating the received signal x(t), creating height models x_h signals based on profile heights, that is the supersposition of the 4 waveforms which spread across several micro-seconds from a 100 ns pulse, which follows from figure 9 which is a real radar return from the Point of the Mountain site. The final step is to perform a correlative procedure on these estimated height waveform models with the collected or estimated actual waveform.

The received signal from the collection platform, or in our case this is a super position of the four rays as described analytically in equation (1). Equation (1) relies on the patch amplitude and differential phase.

$$\hat{x}_{mnp}(t_k) = \sum_{x=1}^{N_x}\sum_{y=1}^{N_y}\sum_{s=1}^{4} A_{mnps}(t_k)\, a[\Delta t_{baseline} - \Delta t_{mps}]\exp(j2\pi[\Delta f_{baseline} - \Delta f_{nps}]) + \eta_{mnp}(t_k) \qquad (1)$$

Furthermore the received amplitude, A_{mnps}, is simply the square root of the bistatic radar equation, which is developed for the MTP algorithm, as seen in Figure 10. The bistatic radar equation for received power is proportional to the backscattering coefficient $\sigma(\theta_\iota,\theta_s)$. The angle θ_ι is the angel of incidence and θ_s is the angle of scattering, Figure 12.

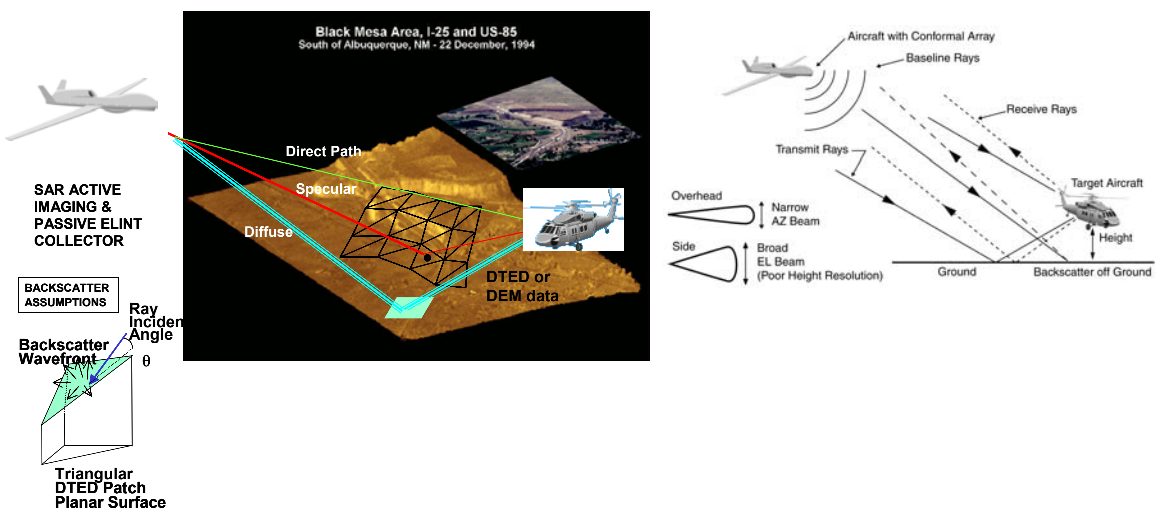


Figure 8. The general concept of the Matched Terrain Processing approach which includes superpositioning the signal measurement of the direct path, strong multipath [specular echoes from a single terrain point], and clutter [diffuse echoes from a wide area of many terrain patches].

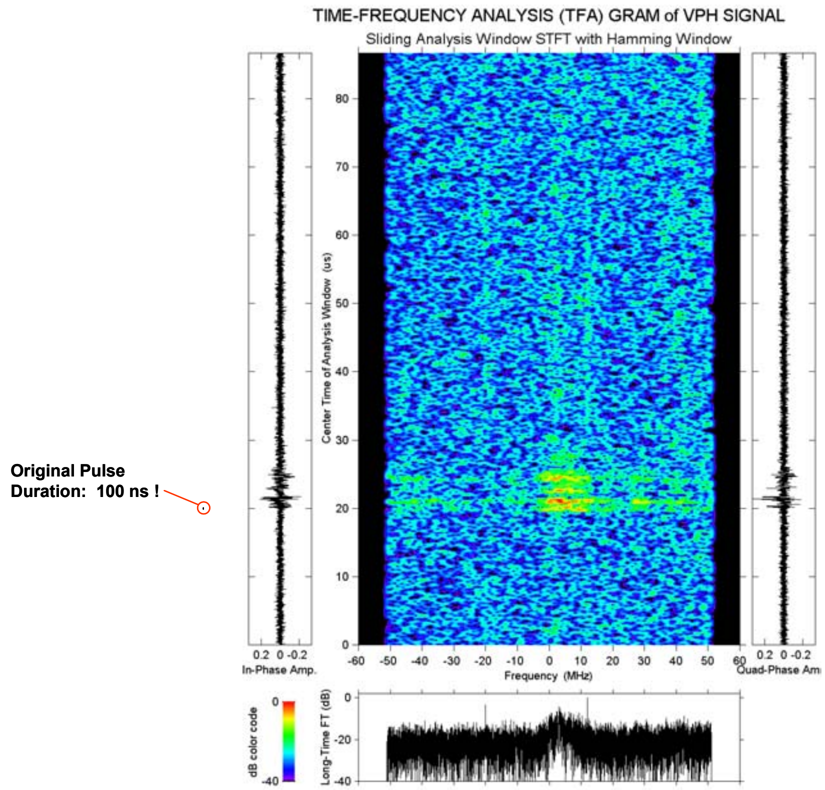


Figure 9. An illustration of a received waveform from an actual field test, where a 100 ns pulse has a return of several micro-seconds.

A radar equation was required for the MTP algorithm that took into account the 4 different rays and applied accordingly. We developed this from first principals of power and power density. The two single hops off the terrain and off the target will be proportional to $1/R^4$ while the other two three hoppers will be proportional on the order of $O(1/R^4)$ while the target is close to the ground and be proportional to $O(1/R^6)$ while the target is gains altitude.

We have made some simplifying assumption for Phase I SBIR effort as follows:

- Surface interaction only as oppose to volume (penetration into the terrain)
- Target initially a point source, so the effective area of the backscatter is only a function of frequency (i.e., $\sigma_{eff}(f)$<1)
- Assuming isotropic radiation pattern (i.e., uniform density in all directions) so the power surface density = $\frac{P_x}{4\pi r_x^2}$, where P_x is power
- Using DETD level 4 (3.5 m resolution) so the area of a patch = .5bh = 6.125 m^2
- The backscatter coefficient is only a function of aspect angle of only the elevation relative to the normal and frequency [$\sigma(\theta_{in}, f)$].

Therefore each height will have an estimated waveform that will be sent through a correlative procedure as in equation (2) where in practice the x(tk) is the real collected waveform and the xh(tk) are the estimated height waveform models.

$$MTP_{correlation} = \sum_{k=1}^{N} x(t_k)x_h(t_k) \tag{2}$$

The height model that best resembles the actual received waveform should have the largest value when entered in equation 2.

A critical component of our effort is to accurately characterize the backscatter off both the terrain patches and the target. Figure 10 is representative of the angles when they are reflecting off a flat surface. For our terrain patches, a rotation and translation will be necessary.

For the purposes of our Phase I effort we will take the relative angle between the angle of incidence and angle of scattering determined from ray theory and use that to determine the energy loss due to the target (a point source in Phase I) and the terrain patches. Furthermore, the helicopter is assumed to have an energy loss of $1/R^2$ while the terrain scattering angles are created using a look up table from Ulaby and Dobson.[1]

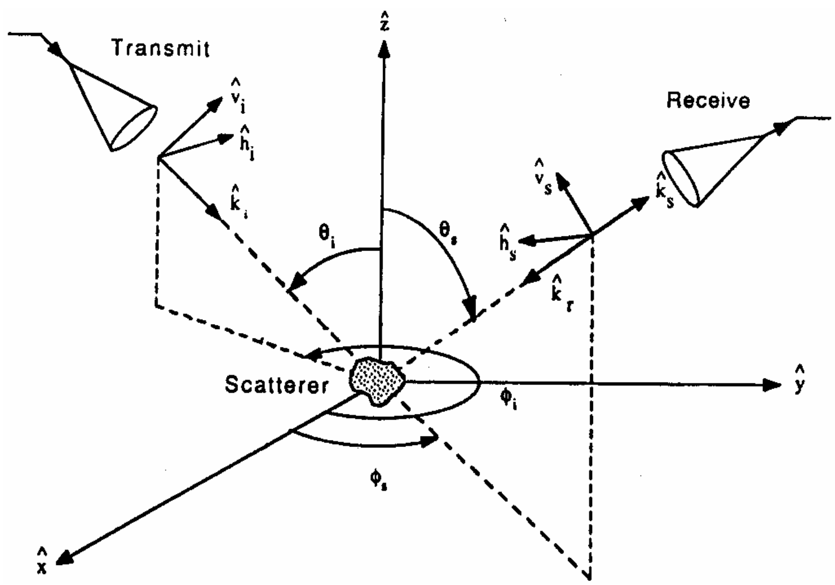


Figure 10. A geometric interpretation of the angle of incidence and angle of scatter on a flat surface. For our purpose this model would be translated based on the some DTED database.

A key component of our approach is to use terrain patches and as seen in Figure 8, we define a terrain patch as a triangular patch. The more patches we use the more accurate the correlation with a received waveform and Figure 11 shows the effects of the terrain patch density and its

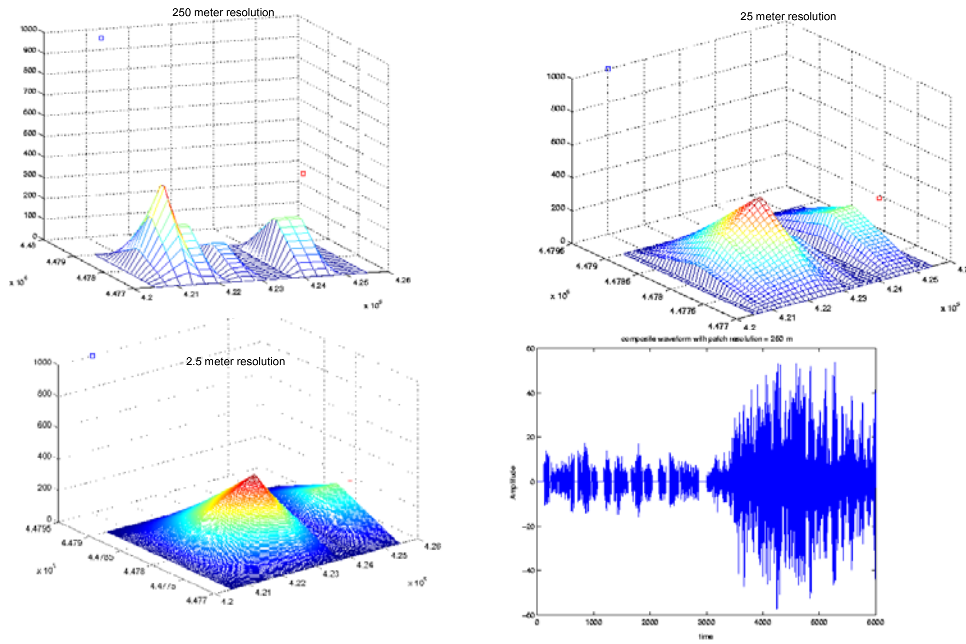


Figure 11. The scenario with different numbers of patches and patch dimensions. Top left, top right, and bottom left have dimensions of 2.5 x 2.5 meters (~90k patches), 25 x 25 meters (3200), and 250 x 250 meters (324).

effect on the estimated waveform, where fewer patches lead to gaps in the estimated waveform models will poorly correlate with an actual waveform. The catch is that with more patches we get a better correlation, but with more patches comes increased computational burden.

SIMULATION AND RESULTS

A simulation was performed in MATLAB to verify the MTP height finding algorithms performance. The simulations were very specific to the scenario described above. We varied the number of terrain patches and target position. In the following, we will show the four different return waveforms, and the matched terrain correlation.

The objective of this simulation is to create estimated height models waveforms from 4 different returns, as seen in Figure 2 with patches, and randomly perform matched terrain correlation operation to determine which height model best correlates to the true height as illustrated in Figure 12. These estimated waveforms are generated over an interval in millisecond centered about the round trip delay from the direct scatter off the target. Three of the four waveforms rely on interaction with the terrain, which is divided up into triangular patches. Therefore each ray interfacing with the terrain, gets a contribution across all patches at that instance in time.

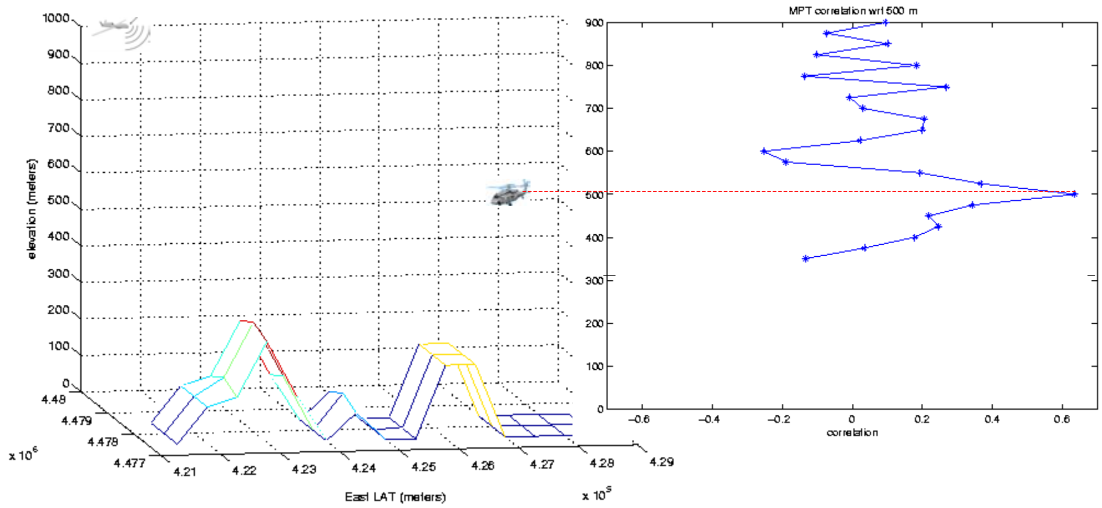


Figure 12. The concept of the Matched correlation procedure of height estimation where a variety of different estimated height waveforms are correlated with a actual received one and the one that best fits the height model has a peak as seen at height 500 meeters.

As seen in Figure 6, we used an X-band radar of 10 GHz with a bandwidth of 10 MHz and looked at an intervals of 2-6 microsecond around the reference time of the (D-D) returns time delay. The four different estimated waveforms are seen for two different heights. The first one is the direct return from hitting the target, the second and third are the bounces off the terrain and the target and the fourth is a single bounce off the terrain. The waveforms are align in time from what we expect, that is the second and third waveforms should start after the direct hit off the target but have a higher amplitude for heights closer to the ground, where as the fourth ray off the terrain only has contribution over the entire time interval if enough patches are used.

The Correlation procedure illustrated in Figure 13 is uses 25 meter height resolution and the correct height is the maximum correlated value.

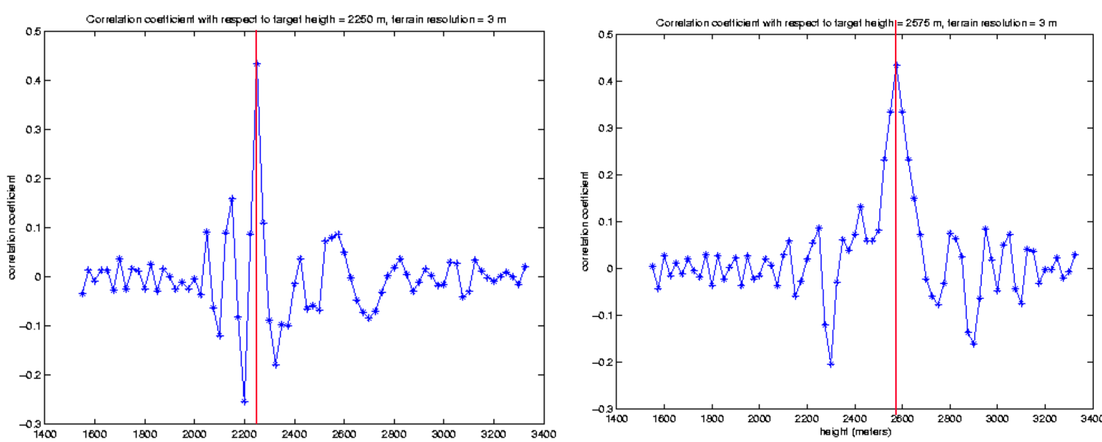


Figure 13. The correlation procedure for two different heights. The peaks line up with the actual heights.

CONCLUSIONS

In this Phase I SBIR effort we used real DETD level 4 data and real backscatter coefficients whos angles are determined from Ray theory. We created a specific scenario and estimated height waveform models and performed a correlative procedure on the estimated superpositioned height waveform models and the result showed that we correlated to the proper height.

The intent of these objectives is to produce, starting from the proof-of-concept demonstration in the Phase I effort, a fully tested and validated geospatial database knowledge-aided technique for real-time embedding in an actual collector radar system at the end of the Phase II effort.

VII. REFERENCES

[1] Ulaby, F. and Dobson, M.; "Handbook of Radar Scattering Statistics for Terrain", Artech house, 1989